GLAST
Science and Instruments

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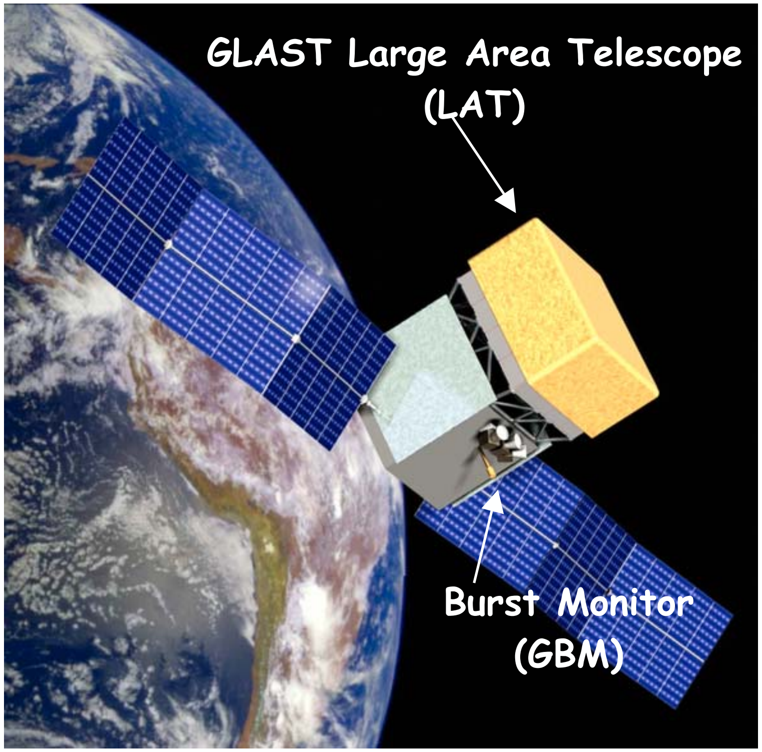
Why study γ's?

Gamma rays carry a wealth of information:

- γ rays do not interact much at their source: they offer a direct view into Nature's largest accelerators.
- similarly, the Universe is mainly transparent to γ rays: can probe cosmological volumes. Any opacity is energy-dependent.
- conversely, γ rays readily interact in detectors, with a clear signature.
- γ rays are neutral: no complications due to magnetic fields. Point directly back to sources, etc.



Two GLAST instruments:

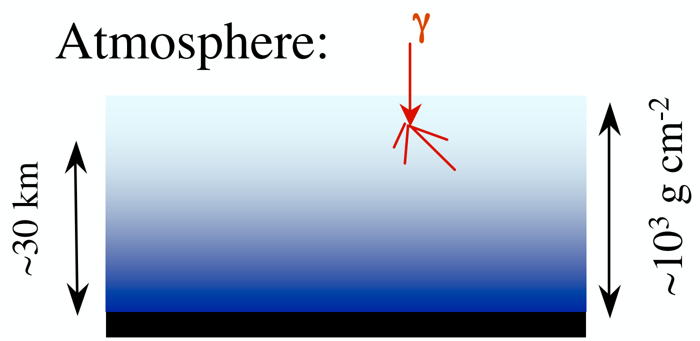
LAT: 20 MeV – >300 GeV

GBM: 10 keV – 25 MeV

Launch: 2006

Cosmic γ-ray Measurement Techniques

Atmosphere:



For E_γ < ~ 100 GeV, must detect above atmosphere (balloons, satellites)

For E_γ > ~100 GeV, information from showers penetrates to the ground (Cerenkov, air showers)

Photon interaction mechanisms:

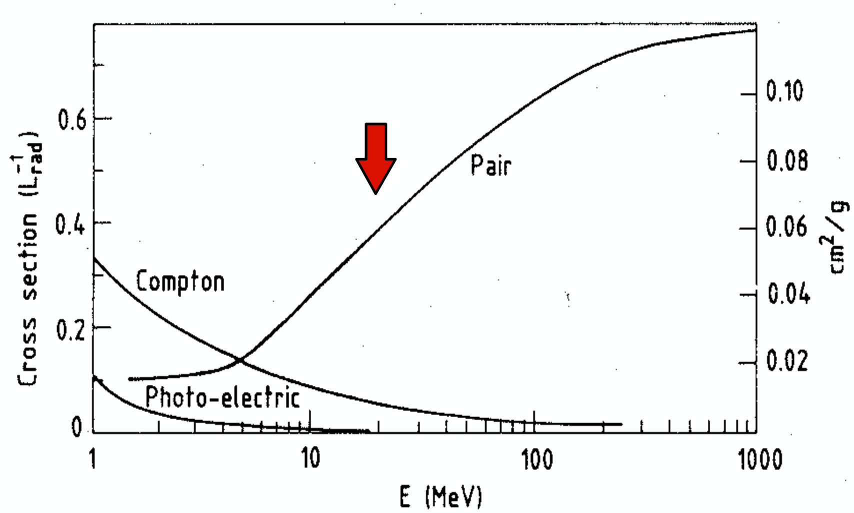


Fig. 2: Photon cross-section σ in lead as a function of photon energy. The intensity of photons can be expressed as $I = I_0 \exp(-\sigma x)$, where x is the path length in radiation lengths. (Review of Particle Properties, April 1980 edition).

Note:

1 MeV=10^6 eV

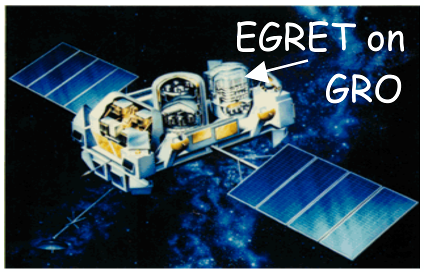
1 GeV=10^9 eV

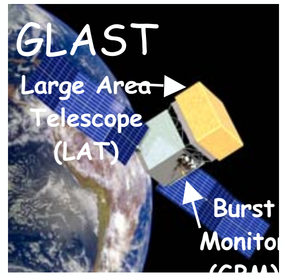
1 TeV=10^{12} eV

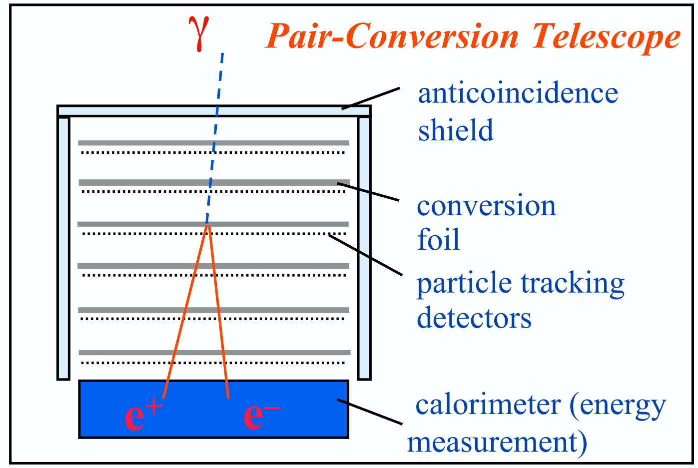
1eV=1.6×10^{-19} Joules

Gamma-ray Experiment Techniques

- **Space-based:**
  - use pair-conversion technique



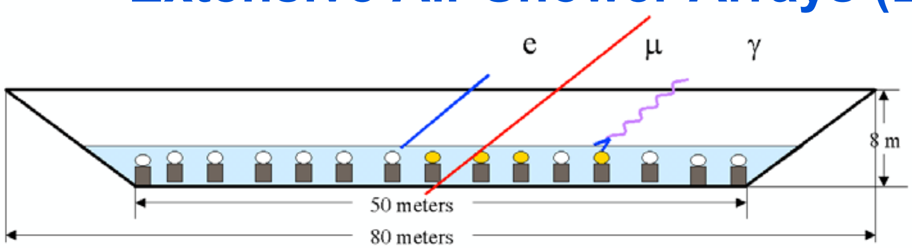




- **Ground-Based:**
  - Airshower Cerenkov Telescopes (ACTs)

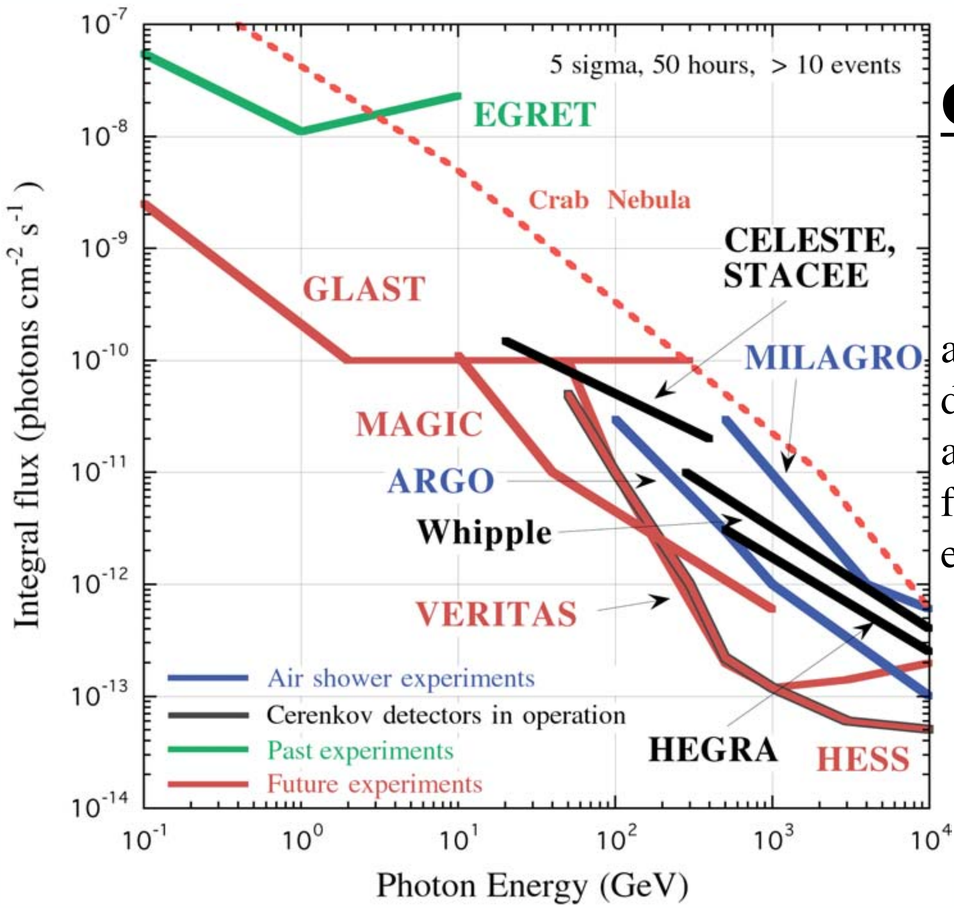
image the Cerenkov light from showers induced in the atmosphere. Examples: Whipple, STACEE, CELESTE, VERITAS

  - Extensive Air Shower Arrays (EAS)



Directly detect particles from the showers induced in the atmosphere. Example: MILAGRO

Gamma-ray Observatories

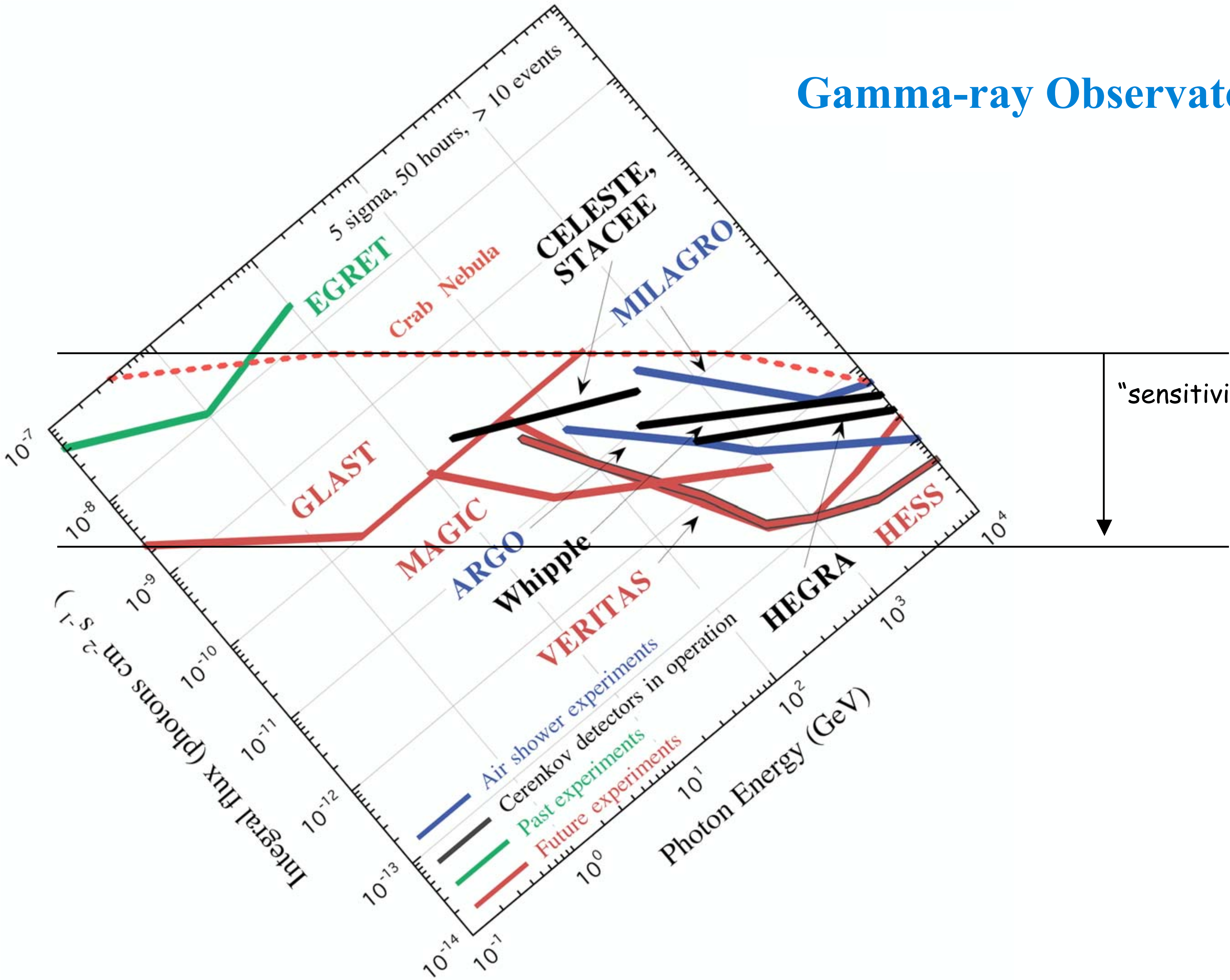


Complementary capabilities

	ground-based		space-based
	ACT	EAS	Pair
angular resolution	good	fair	good
duty cycle	low	high	high
area	large	large	small
field of view	small	large	large+can reorient
energy resolution	good	fair	good, w/ smaller systematic uncertainties

The next-generation ground-based and space-based experiments are well matched.

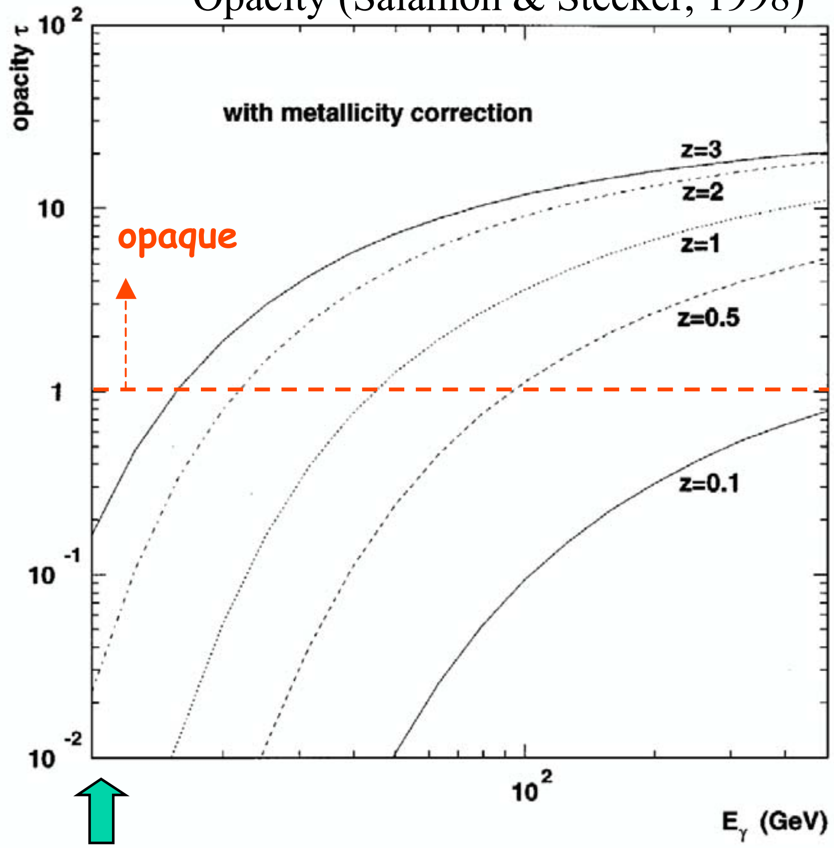
Gamma-ray Observatories



An Important Energy Band for Cosmology

Photons with E>10 GeV are attenuated by the diffuse field of UV-Optical-IR extragalactic background light (EBL)

Opacity (Salamon & Stecker, 1998)



No significant attenuation below ~10 GeV.

only $e^{-\tau}$ of the original source flux reaches us

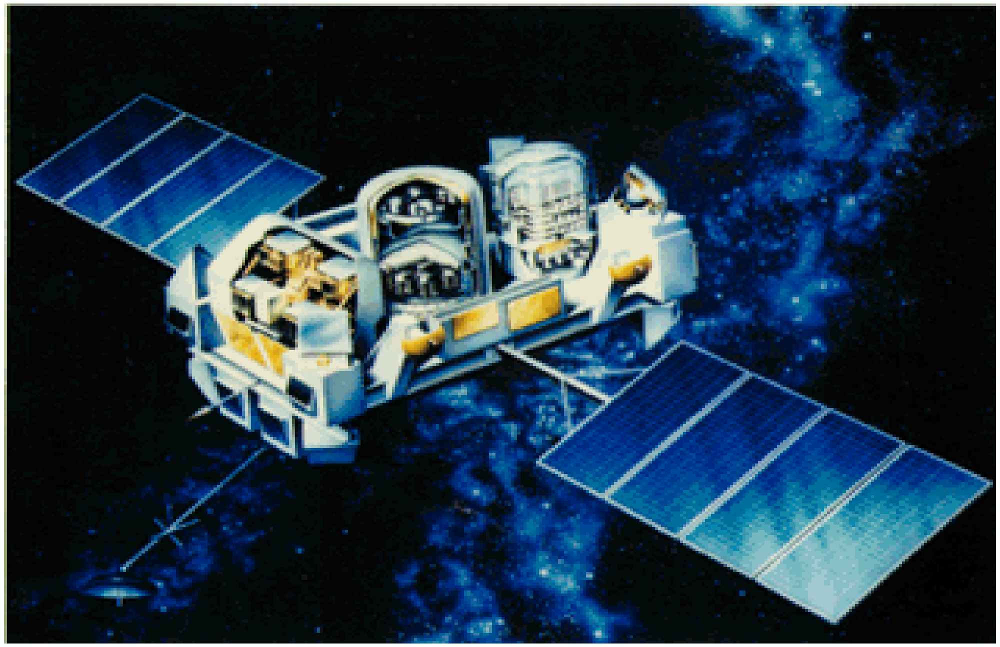
EBL over cosmological distances is probed by gammas in the 10-100 GeV range. Important science for GLAST!

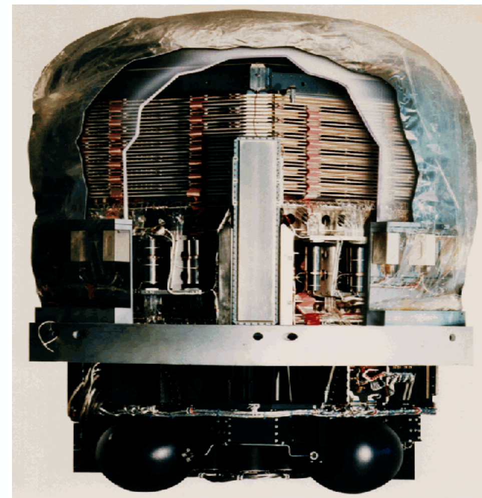
In contrast, the TeV-IR attenuation results in a flux that may be limited to more local (or much brighter) sources.

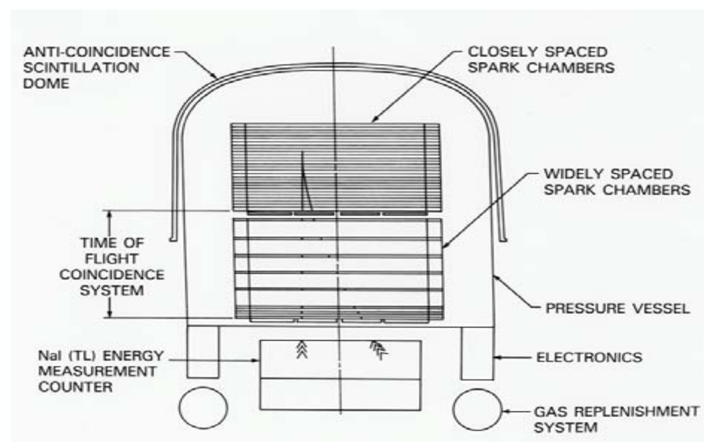
A dominant factor in EBL models is the time of galaxy formation -- attenuation measurements can help distinguish models.

EGRET

The high energy gamma ray detector on the Compton Gamma Ray Observatory (20 MeV - ~20 GeV)







The Success of EGRET: Probing New Territory

History:

SAS-2, COSB (1970's-1980's) exploration phase: established galactic diffuse flux

EGRET (1990's) established field:

- increased number of ID'd sources by large factor;
- broadband measurements covering energy range ~20 MeV - ~20 GeV;
- discovered many still-unidentified sources;
- discovered surprisingly large number of Active Galactic Nuclei (AGN);
- discovered multi-GeV emissions from gamma-ray bursts (GRBs);
- discovered GeV emissions from the sun

GLAST will explore the unexplored energy range above EGRET's reach, filling in the present gap in the photon spectrum, and will cover the very broad energy range ~ 20 MeV - 300 GeV (→ 1 TeV) with superior acceptance and resolution. Historically, opening new energy regimes has led to the discovery of totally unexpected new phenomena.

GLAST Science

GLAST will have a very broad menu that includes:

- Systems with supermassive black holes
- Gamma-ray bursts (GRBs)
- Pulsars
- Solar physics
- Origin of Cosmic Rays
- Probing the era of galaxy formation
- Discovery! Particle Dark Matter? Hawking radiation from primordial black holes? Other relics from the Big Bang? Testing Lorentz invariance. New source classes.

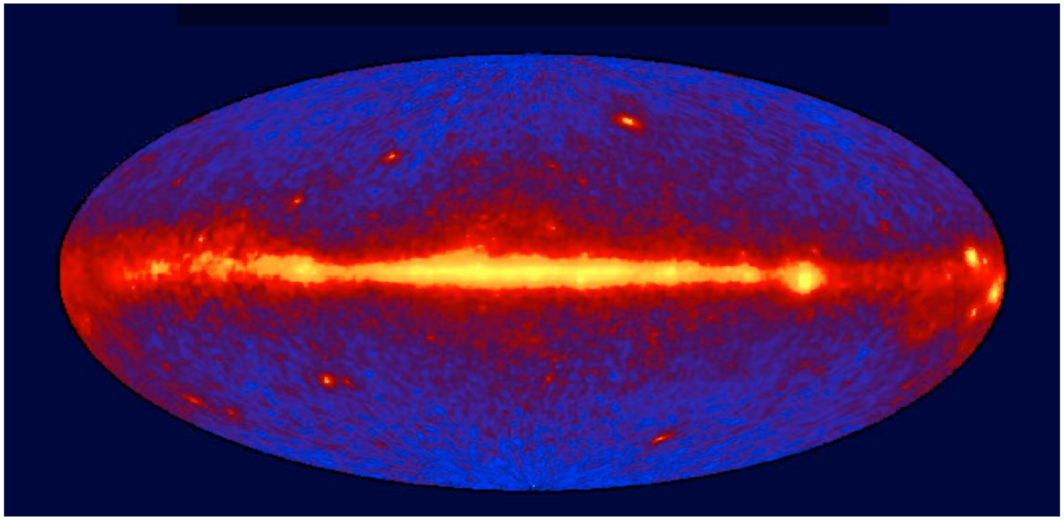
Huge increment in capabilities.

GLAST draws the interest of both the the High Energy Particle Physics and High Energy Astrophysics communities.

GLAST LAT High Energy Capabilities

- Huge FOV (~20% of sky)
- Broadband (4 decades in energy, including unexplored region > 10 GeV)
- Unprecedented PSF for gamma rays (factor > 3 better than EGRET for E>1 GeV)
- Large effective area (factor > 4 better than EGRET)
- **Results in factor > 30-100 improvement in sensitivity**
- No expendables → long mission without degradation

Features of the gamma-ray sky



EGRET all-sky survey (galactic coordinates) E>100 MeV

diffuse extra-galactic background (flux ~ 1.5×10^{-5} $cm^{-2}s^{-1}sr^{-1}$)

galactic diffuse (flux ~O(100) times larger)

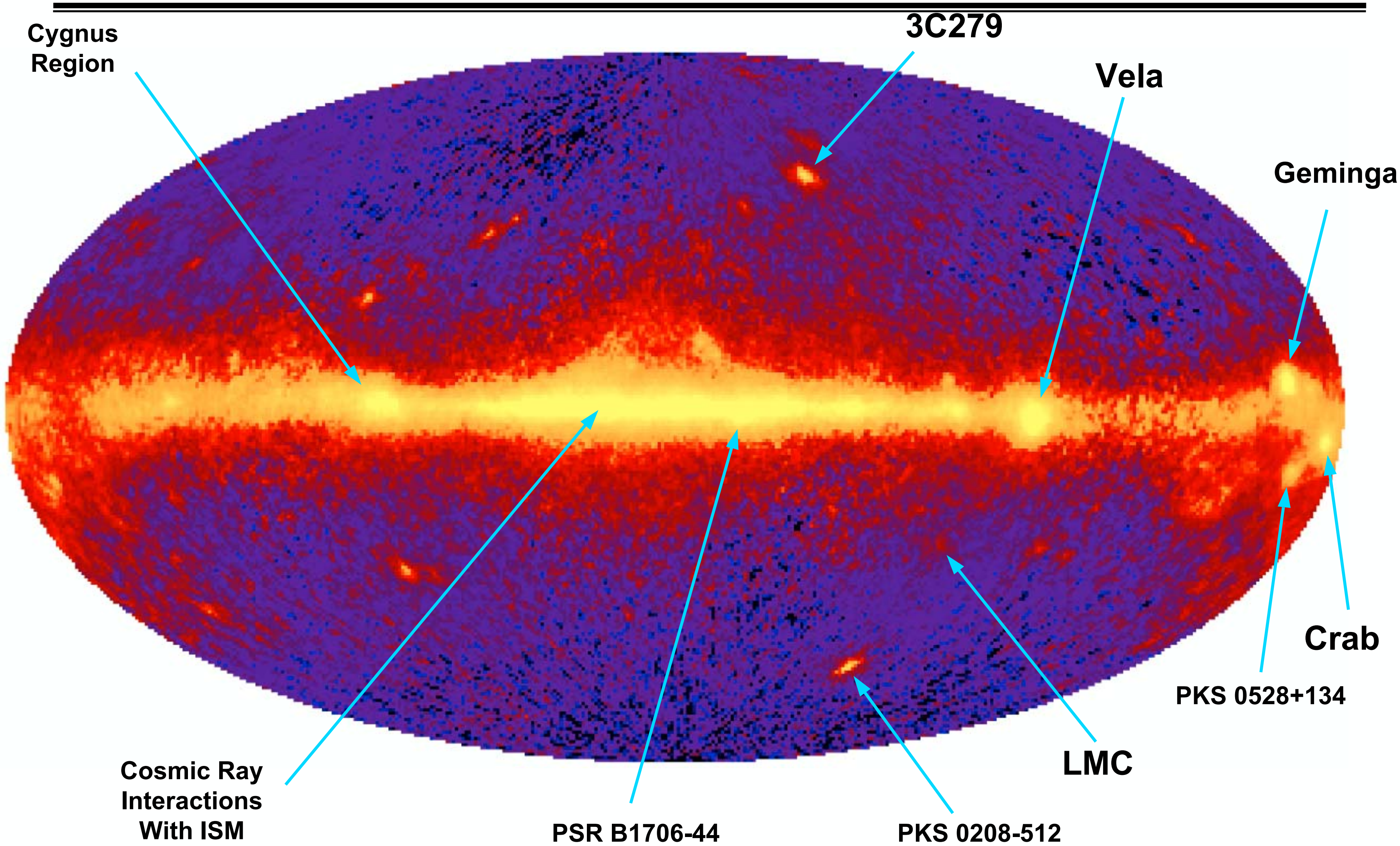
high latitude (extra-galactic) point sources (typical flux from EGRET sources O(10^{-7} - 10^{-6}) $cm^{-2}s^{-1}$

galactic sources (pulsars, un-ID'd)

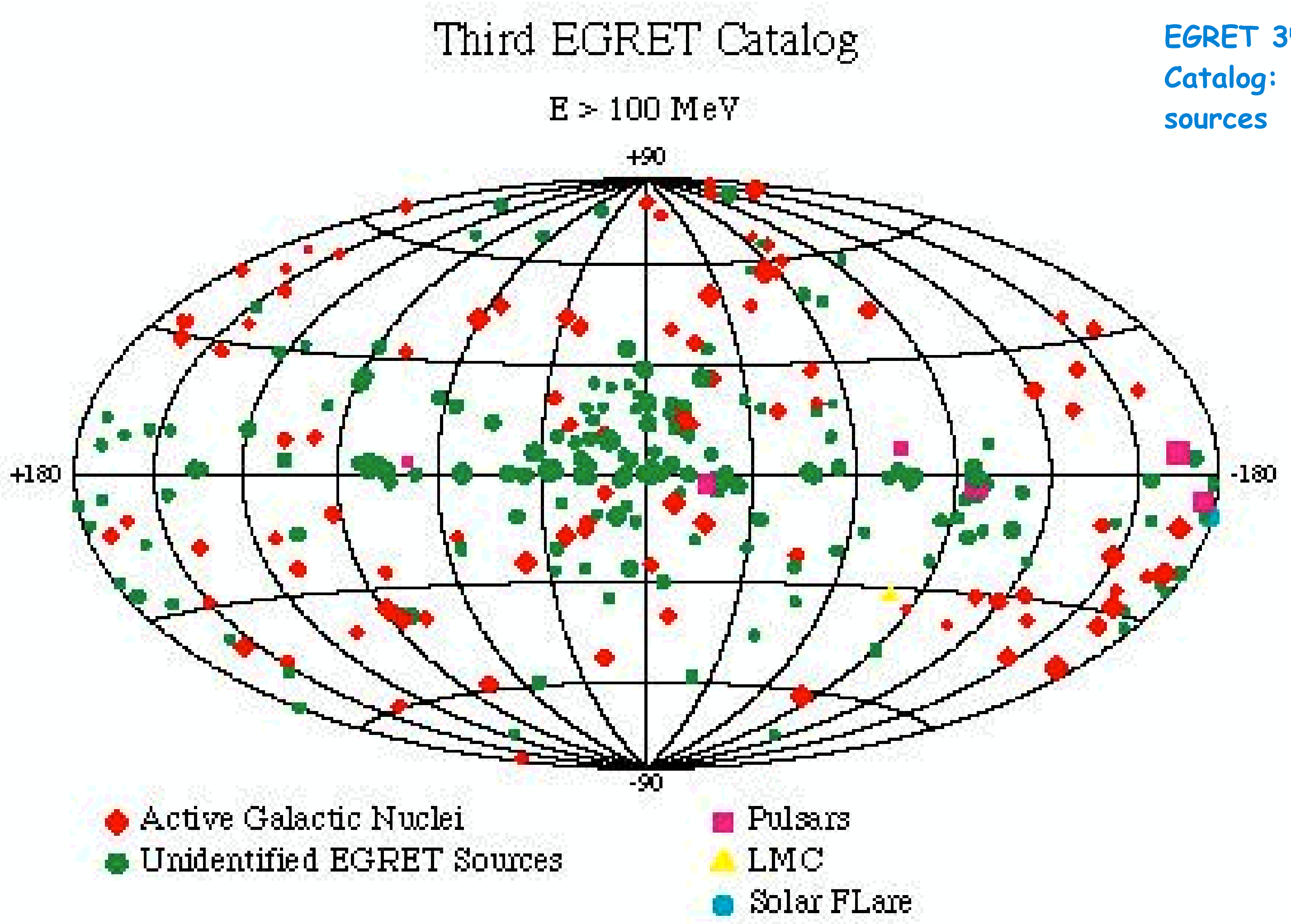
An essential characteristic: VARIABILITY in time!

⇨ Field of view, and the ability to repoint, important for study of transients.

EGRET All Sky Map (>100 MeV)

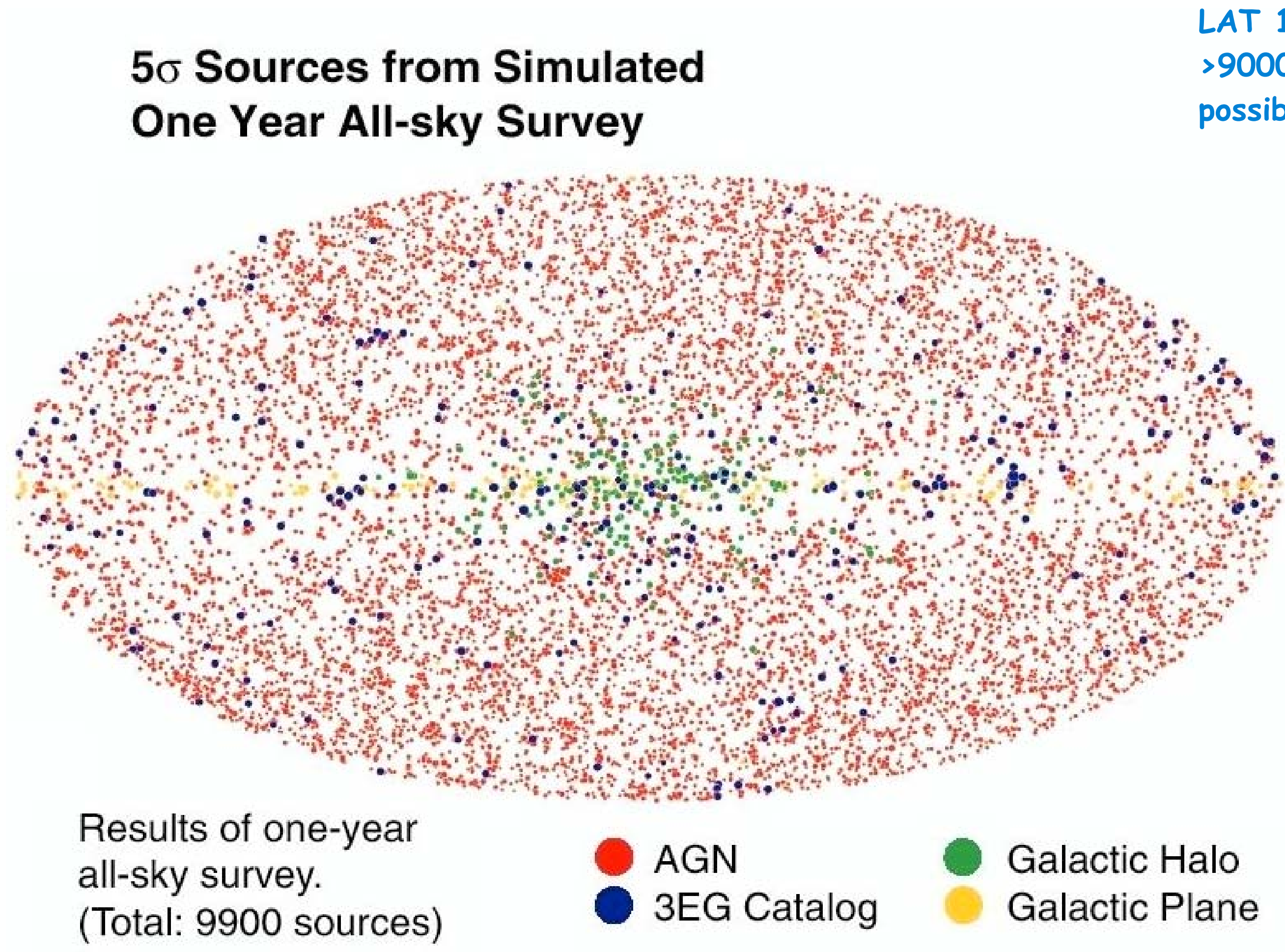


Sources



EGRET 3rd Catalog: 271 sources

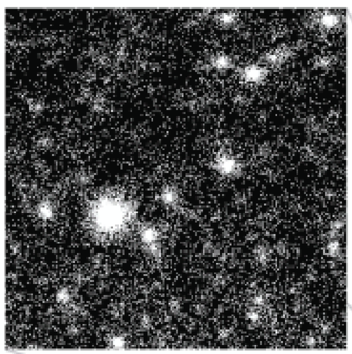
Sources



LAT 1st Catalog:
>9000 sources
possible

Diffuse Extra-galactic Background Radiation

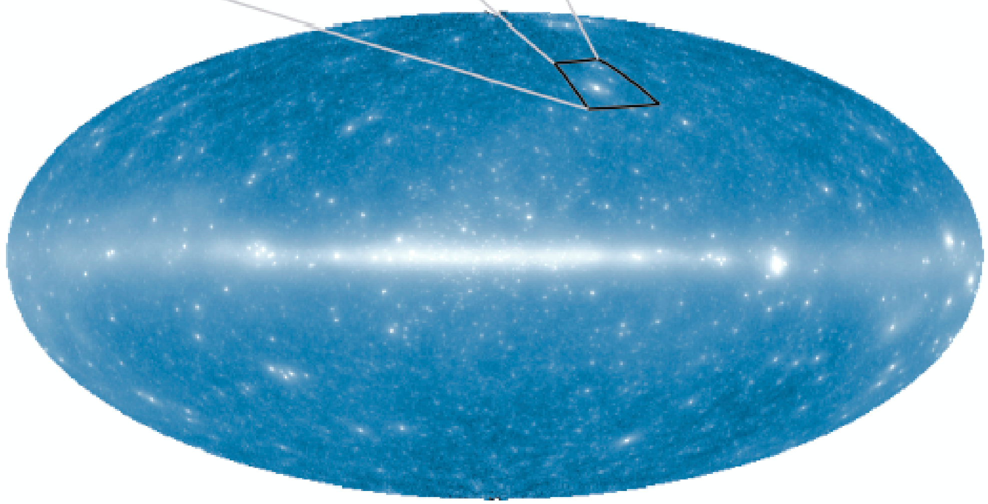
Is it really isotropic (e.g., produced at an early epoch in intergalactic space) or an integrated flux from a large number of yet unresolved sources? GLAST has much higher sensitivity to weak sources, with better angular resolution.



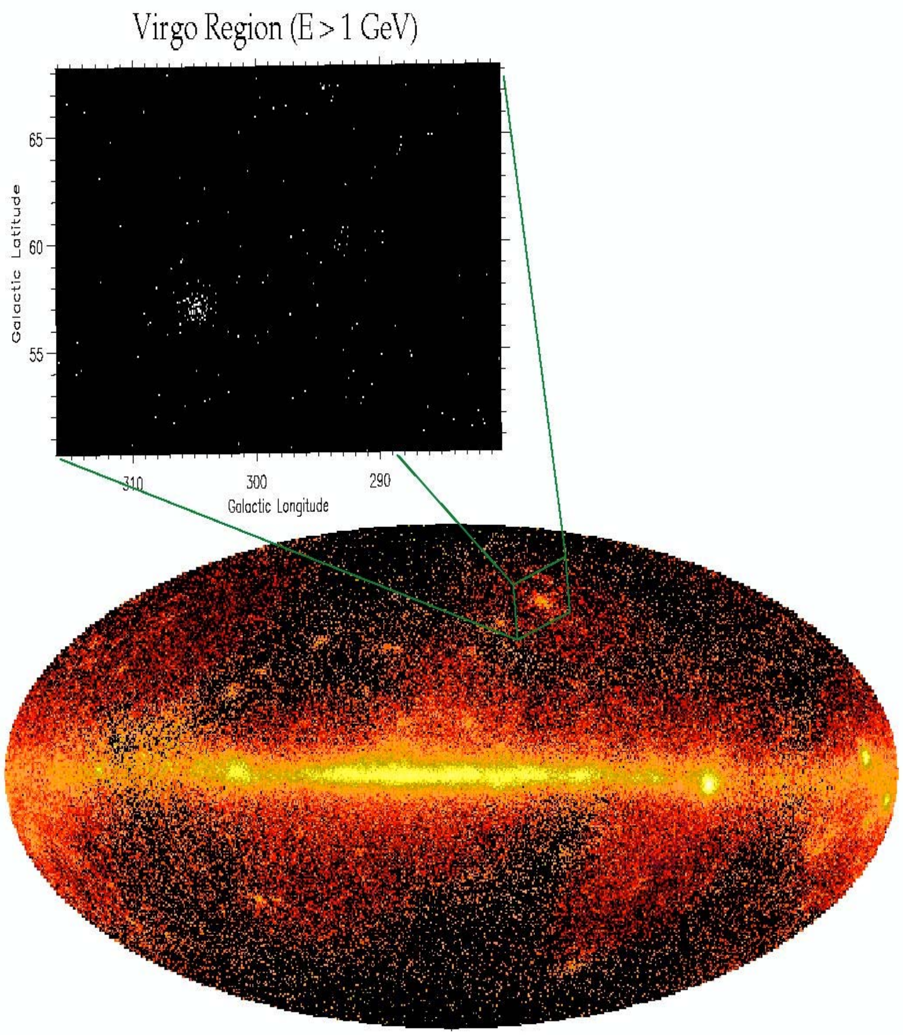
E > 1 GeV Map

GLAST will bring alive the HE gamma-ray sky.

Simulated LAT One Year All-sky map (E > 100 MeV)



The origin of the diffuse extragalactic gamma-ray flux is a mystery. Either sources are there for GLAST to resolve (and study!), OR there is a truly diffuse flux from the very early universe.



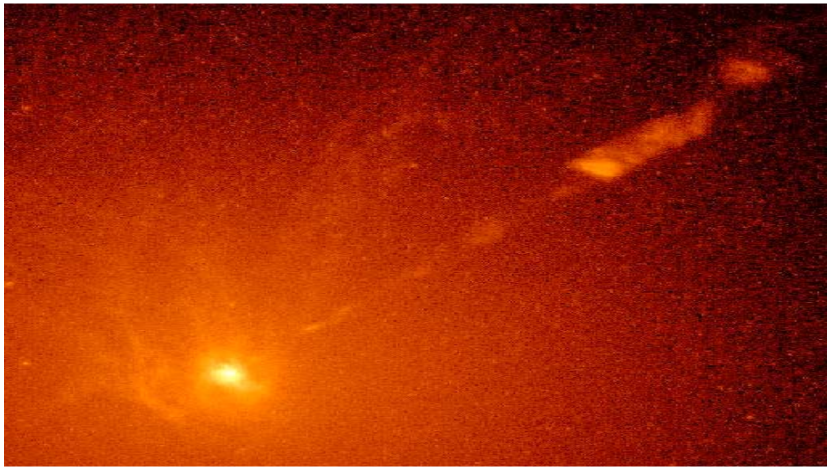
EGRET One-Year All-Sky Survey (E > 100 MeV)

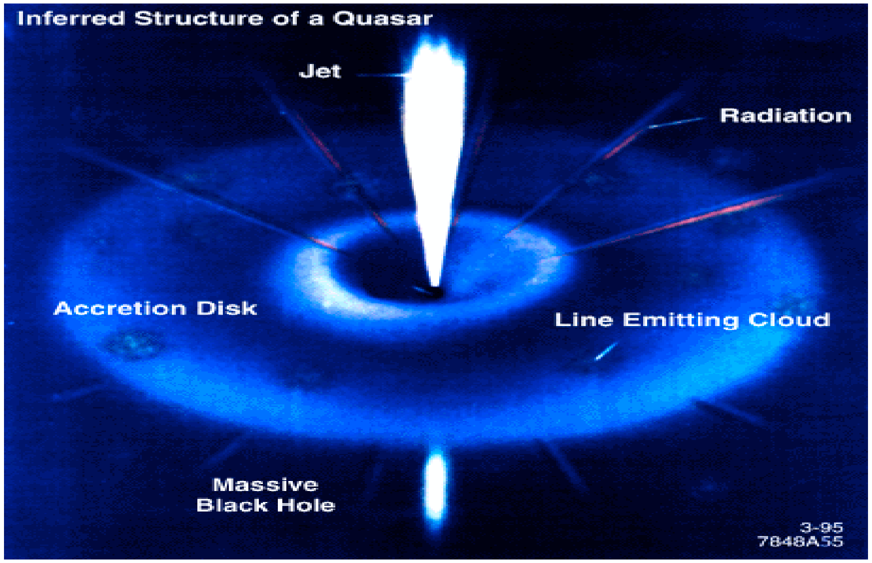
Active Galactic Nuclei (AGN)

Active galaxies produce vast amounts of energy from a very compact central volume.

Prevailing idea: powered by accretion onto super-massive black holes (10^6 - 10^{10} solar masses). Different phenomenology primarily due to the orientation with respect to us.

HST Image of M87 (1994)



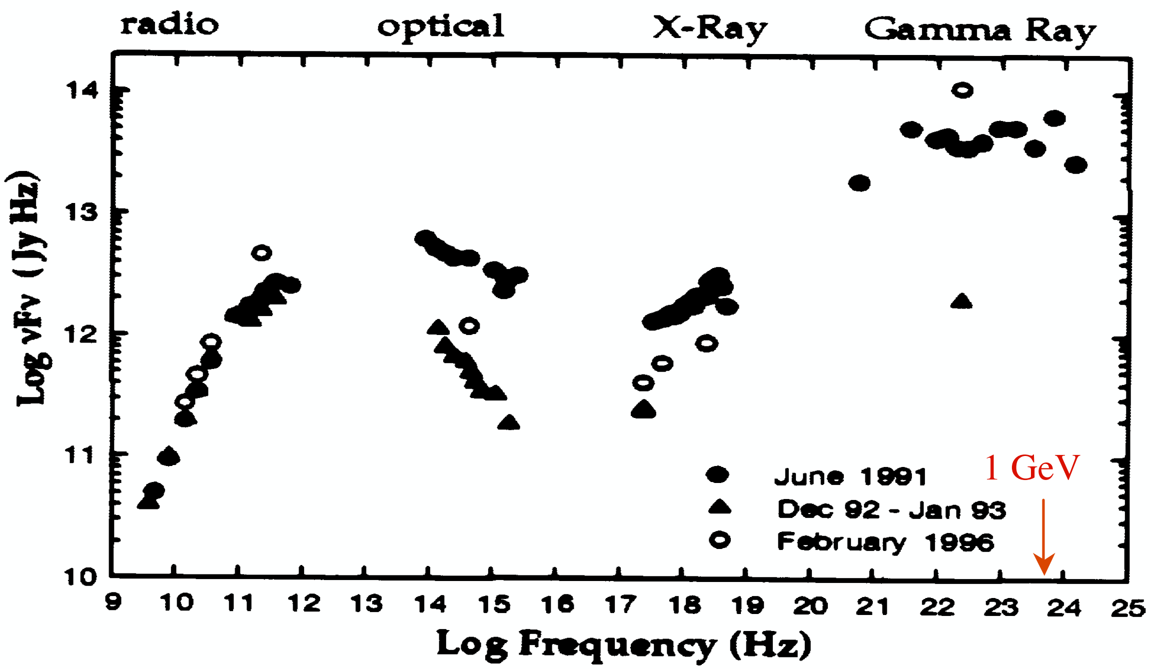


Models include energetic (multi-TeV), highly-collimated, relativistic particle jets. High energy γ-rays emitted within a few degrees of jet axis. Mechanisms are speculative; γ-rays offer a direct probe.

AGN Shine Brightly in GLAST Energy Range

Power output of AGN is remarkable. Multi-GeV component can be dominant!

Estimated luminosity of 3C 279:
~ 10^{45} erg/s
corresponds to 10^{11} times total solar luminosity
just in γ-rays!! Large variability within days.



Multiwavelength Spectrum of 3C 279

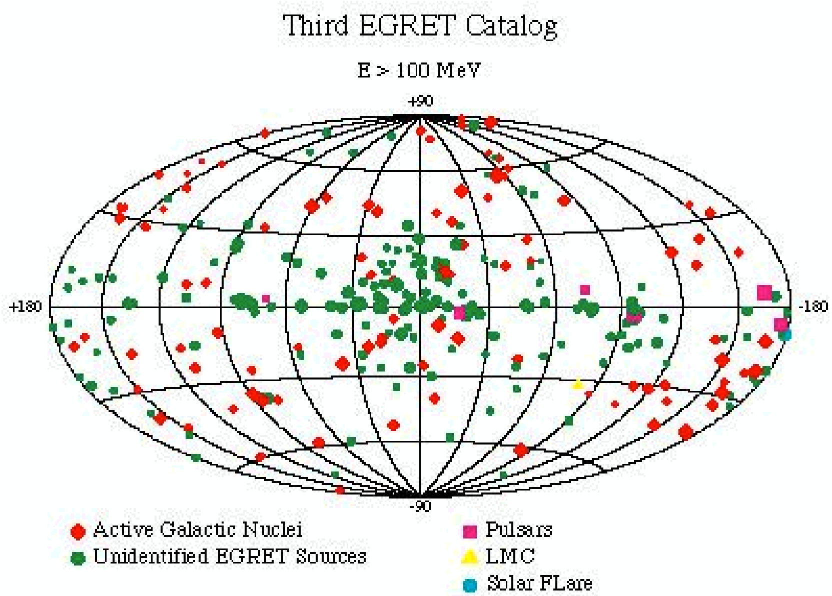
Sum all the power over the whole electromagnetic spectrum from all the stars of a typical galaxy: an AGN emits this amount of power in JUST γ rays from a very small volume!

A surprise from EGRET:

detection of dozens of AGN

shining brightly in

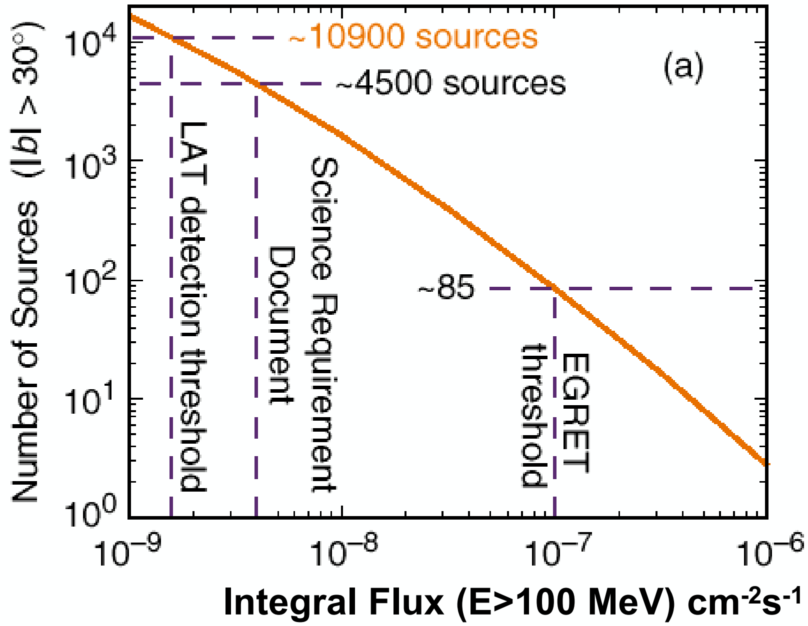
γ-rays -- Blazars



- a key to solving the longstanding puzzle of the extragalactic diffuse gamma flux -- is this integrated emission from a large number of unresolved sources?
- blazars provide a source of high energy γ-rays at cosmological distances. The Universe is largely transparent to γ-rays (any opacity is energy-dependent), so they probe cosmological volumes.

AGN: What GLAST will do

EGRET has detected ~ 70 AGN. Extrapolating, GLAST should expect to see dramatically more – many thousands:

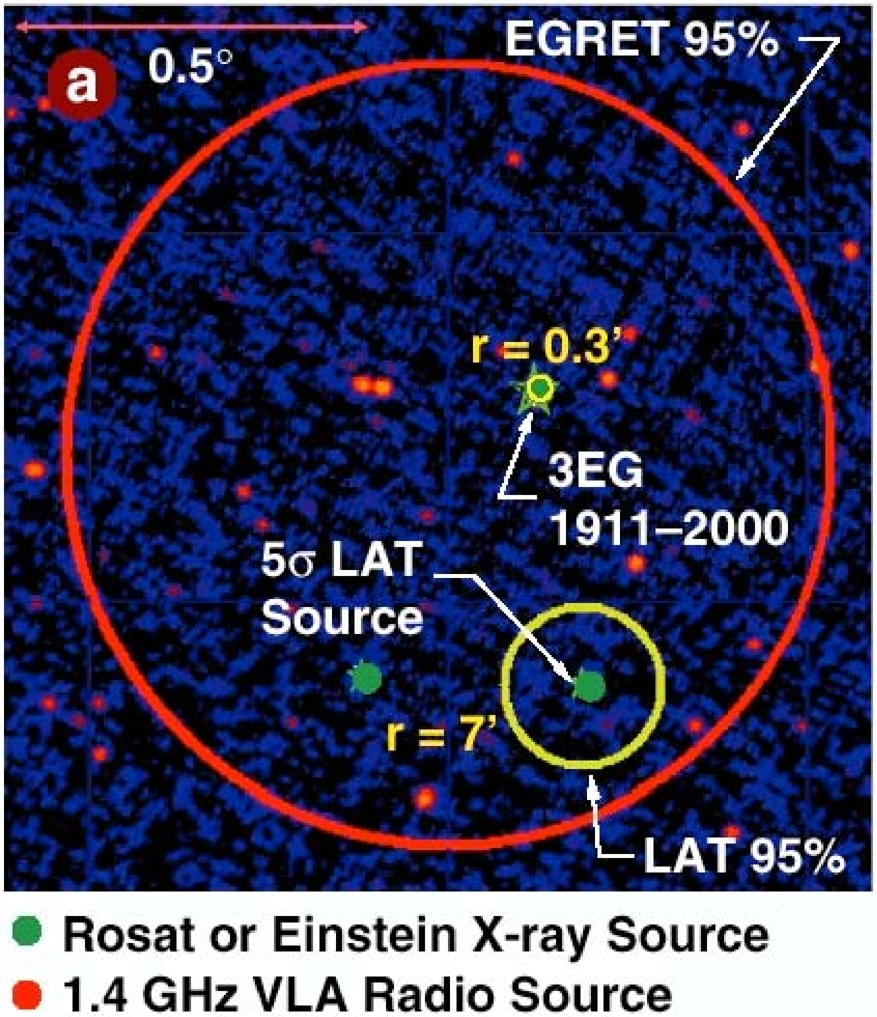


- Allows a statistically accurate calculation of AGN contribution to the high energy diffuse extra-galactic background.
- Constrain acceleration and emission models. How do AGN work?
- Large acceptance and field of view allow relatively fast monitoring for variability over time -- correlate with other detectors at other wavelengths.
- Probe energy roll-offs with distance (light-light attenuation): info on era of galaxy formation.
- Long mission life to see weak sources and transients.

Joining the unique capabilities of GLAST with other detectors will provide a powerful tool.

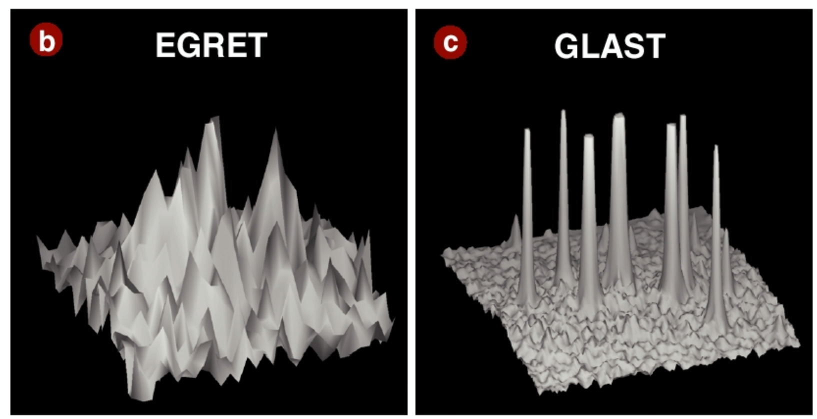
Unidentified Sources

172 of the 271 sources in the EGRET 3rd catalog are "unidentified"



EGRET source position error circles are ~0.5°, resulting in counterpart confusion.

GLAST will provide much more accurate positions, with ~30 arcsec - ~5 arcmin localizations, depending on brightness.

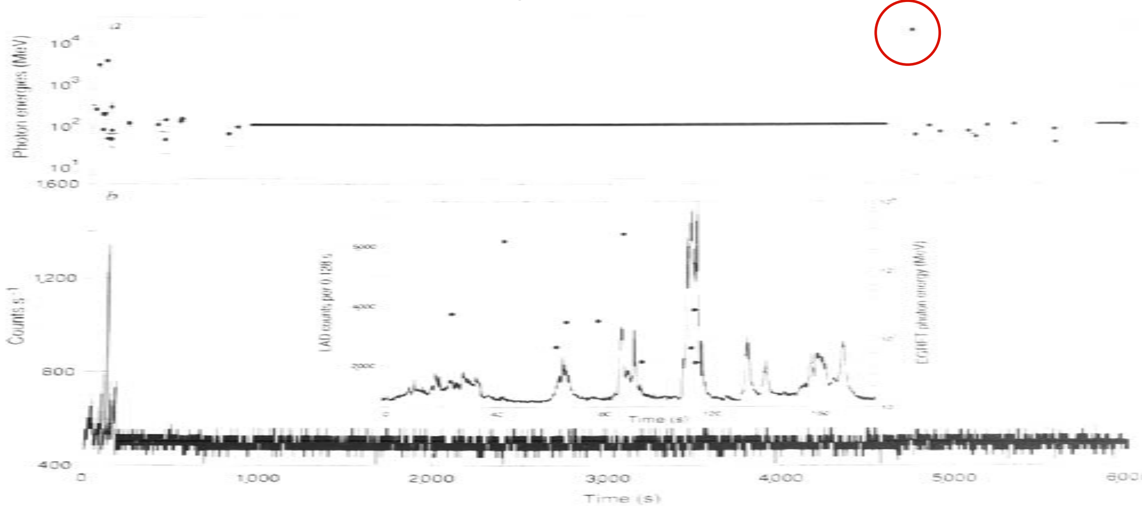


Cygnus region (15x15 deg)

Gamma Ray Bursts

GRBs discovered in 1960's accidentally by the Vela military satellites, searching for gamma-ray transients (guess why!) The question persists : What are they??

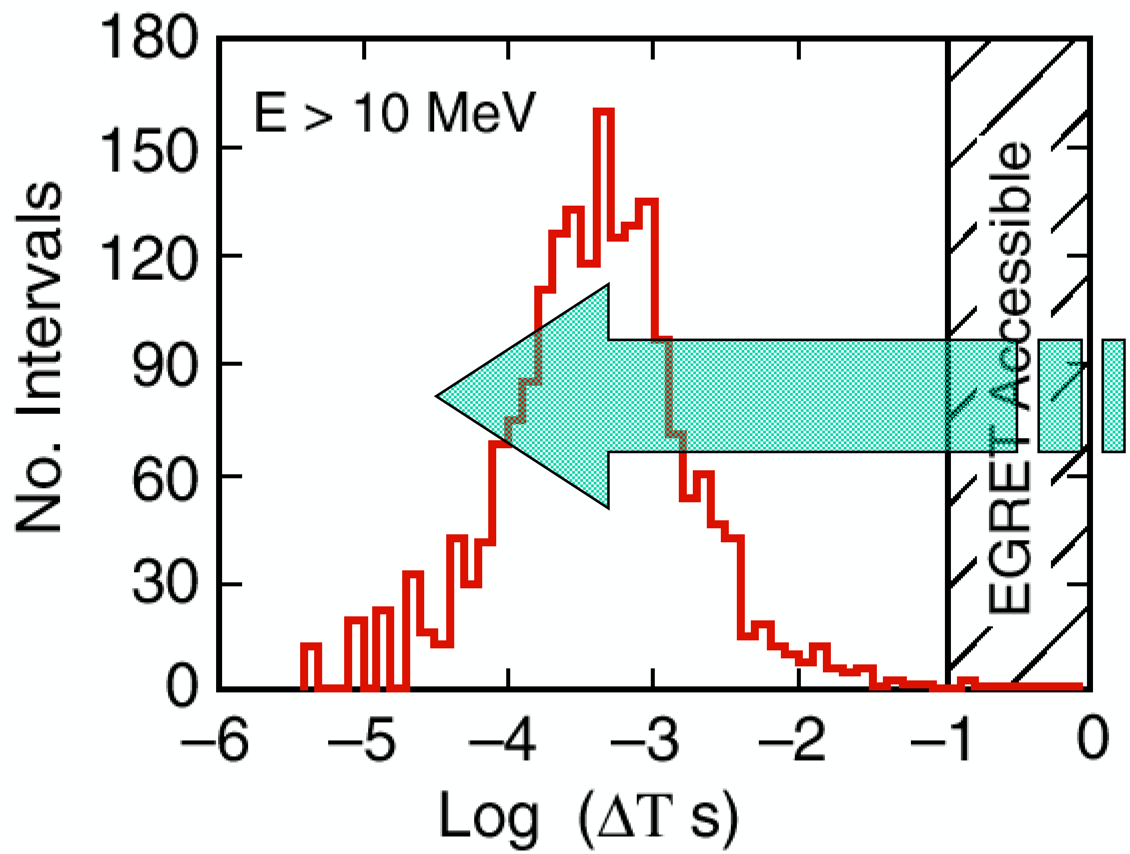
EGRET has detected very high energy emission associated with bursts, including an 18 GeV photon ~75 minutes after the start of a burst:



GLAST will provide definitive information about the high energy behavior of bursts. LAT and GBM together will measure emission over >7 decades of energy.

GRBs and Instrument Deadtime

Distribution for the 20th brightest burst in a year (Norris et al)

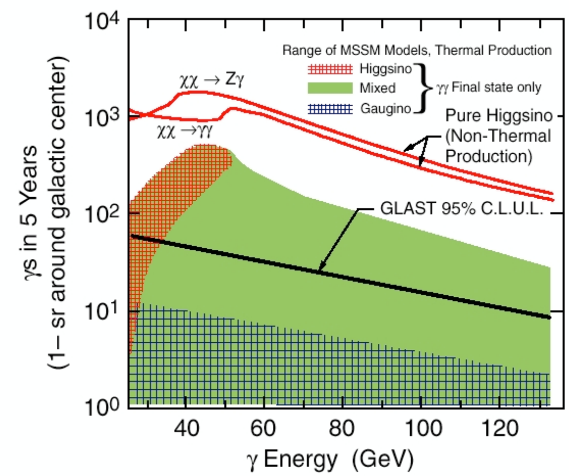


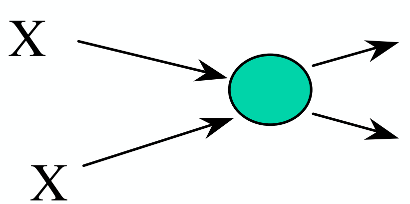
Time between consecutive arriving photons

LAT will open a wide window on the study of the high energy behavior of bursts.

Particle Dark Matter

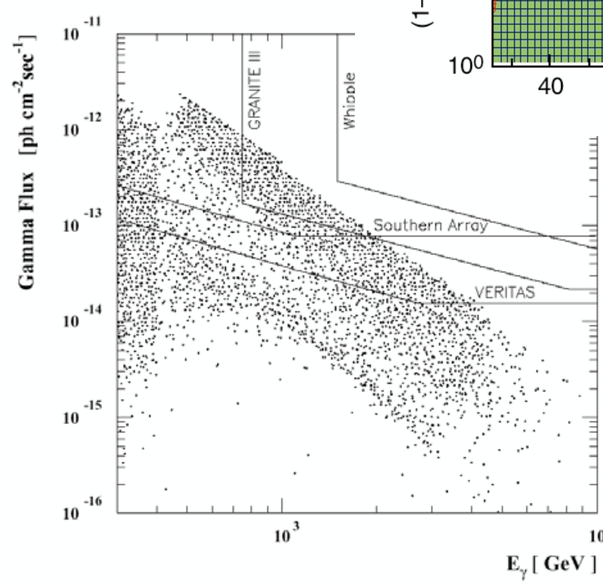
Some important models in particle physics could also solve the dark matter problem in astrophysics. If correct, these new particle interactions could produce an anomalous flux of gamma rays.





or γγ or Zγ

"lines"?



Just an example of what might be waiting for us to find!

PHYSICS

STRING INSTRUMENTS

String theory may soon be testable

The theory of strings, which attributes the infinite variety of the cosmos to the harmonies of subatomic membranes, has emerged over the past two decades as the leading contender for the "theory of everything." It would explain the four forces of nature—gravity, electromagnetism, and the weak and strong nuclear forces—as a single force with different manifestations. But how could such a theory ever be proved? The last time the four forces acted as one was at the big bang; to re-create those conditions, physicists would need a particle accelerator larger than the solar system, which Congress might be reluctant to fund. Despairing of the task, some scientists call theories of everything an exercise in theology. "For the first time since the Dark Ages," physicists Paul Ginsparg and Sheldon L. Glashow wrote 12 years ago, "we can see how our noble search may end, with faith replacing science once again."

That proclamation now seems premature. Researchers have devised the first astronomical probe of theories of everything and have also discovered that the four forces may unite under conditions short of the big bang. "Unification, the theory of everything, might actually be accessible experimentally," says Nima Arkani-Hamed of the Stanford Linear Accelerator Center.

The probe was conceived by Giovanni Amelino-Camelia of the University of Oxford and the Institute of Physics in Neuchâtel, Switzerland, and his colleagues. They propose using gamma-ray bursts to check whether the speed of light in a vacuum depends on its wavelength. According to special relativity, light has the same speed in a vacuum regardless of wavelength. Therefore, the detection of a wavelength-dependent speed would unearth a level of physical law more fundamental than relativity.

Variations in the speed of light are familiar to anyone who has looked at a prism. Because glass, water and other substances allow red light to go faster than blue, the prism splays white light into a rainbow.

Empty space, too, is a substance of sorts. By the laws of quantum mechanics, particles burble in and out of existence as the void fluctuates around complete emptiness. Present quantum theory, which incorporates special relativity but not gravity, says that these fluctuations affect all wavelengths of light equally. But theories of everything also allow for fluctuations in gravity, which might act as subatomic lenses that bend light. The shorter the wavelength of light, the more it might induce such lensing and the slower it would travel.

Although the retardation is predicted to be small, it might show up in gamma-ray bursts. Whatever their mysterious origins, these intense flashes travel billions of light-years and flicker frenetically. The blinking gives astronomers a handle on any dispersion: at shorter wavelengths, a flicker would register a moment after it appeared at longer wavelengths. Across a typical range of gamma rays, the time difference would be around 10 microseconds—not much, considering that the radiation has traveled for 10 billion years. But it may be just enough for current instruments to detect. And the Gamma-ray Large Area Space Telescope, scheduled to begin operation in 2004, will certainly have the requisite resolution.

Meanwhile there is another way that predictions of string theory could be detectable sooner: namely, if the forces of nature unite under unexpectedly mild conditions. Two years ago Edward Witten of the Institute for Advanced Study in Princeton, N.J., and Joseph D. Lykken of Fermi National Accelerator Laboratory in Batavia, Ill., realized that strings could come into play at lesser energies than previously assumed. In other words, maybe strings aren't so tiny.

The standard argument that strings should appear at high energies is based on theoretical extrapolations from the measured strength of the four forces. Electromagnetism and the two nuclear forces should become equally strong at the so-called Grand Unification scale. At a slightly higher energy, the Planck scale, gravity is supposed to join in. Both scales are trillions or quadrillions of times beyond the reach of today's accelerators.

But these extrapolations don't take into account a key prediction of string theory: the presence of extra dimensions, on top of the four familiar ones—three for space, one for time. New dimensions could lower both the Grand Unification scale (as shown recently by Keith R. Dienes, Emilian Dudas and Tony Gherghetta of CERN near Geneva) and the Planck scale (according to Arkani-Hamed, Savas Dimopoulos of Stanford University and Gia Dvali of the Abdus Salam International Center for Theoretical Physics in Trieste).

Specifically, string theory adds six minuscule dimensions, which Dienes compares to hairline cracks in the pavement. Each crack adds an extra (third) dimension to the two-dimensional road, but if it is small, your car rolls right over it.

If the crack is large enough and if your tire is small enough, however, your car rattles. Similarly, if the extra dimensions of space are large enough and a particle is small enough, the particle could begin to vibrate in those dimensions. New harmonics would develop, generating new particles—and altering the way the electromagnetic and the two nuclear forces are transmitted. Gravity might shift in a telltale way, too: for simple geometric reasons, extra dimensions would cause gravity to weaken more rapidly with distance. Experimenters are starting to look for such an effect.

Lower unification scales would allow the Large Hadron Collider, now being built at CERN, to make strings. To be sure, that prospect is still speculative. "All these proposals are in the spirit of 'unlikely to be right, but so extremely interesting if they are that they are well worth thinking about,'" says Sean M. Carroll of the University of California at Santa Barbara. But along with other hints of new physics—the neutrino mass, the cosmological constant, the odd behavior of meson particles [see "The Asymmetry between Matter and Antimatter," on page 76]—they suggest that we won't need to take a theory of everything on faith after all. —*George Musser*

News and Analysis

24 SCIENTIFIC AMERICAN October 1998

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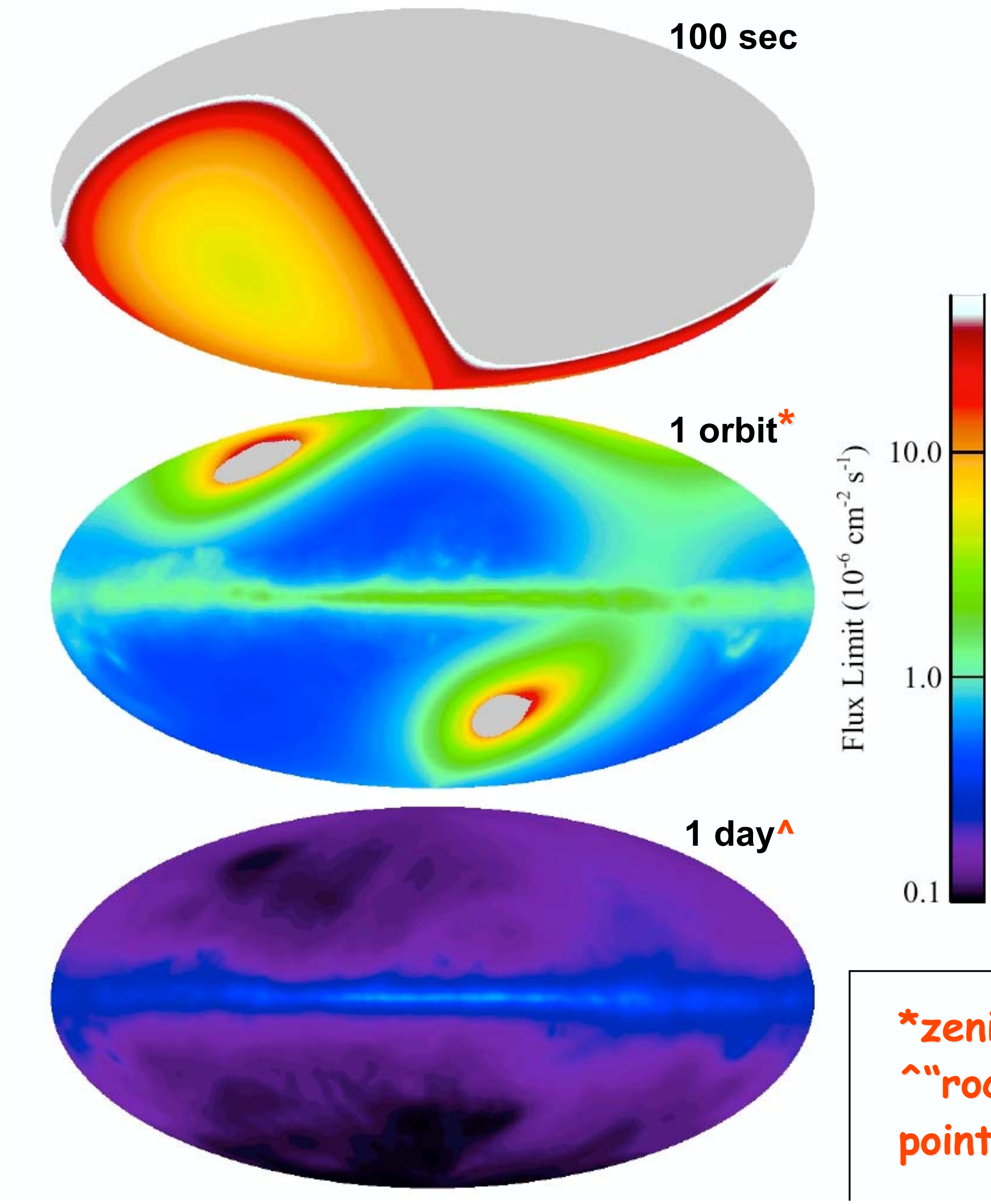
$$V = c\left(1 - \xi \cdot \frac{E}{E_{QG}} + \ldots\right)$$

Amelino-Camelia et al, Ellis, Mavromatos, Nanopoulos

Effects could be O(100) ms or larger, using GLAST data alone. But ?? effects intrinsic to bursts??

Representative of window opened by such distance and energy scales

Transients Sensitivity During All-sky Scan Mode



EGRET Fluxes

- GRB940217 (100sec)
- PKS 1622-287 flare
- 3C279 flare
- Vela Pulsar
- Crab Pulsar
- 3EG 2020+40 (SNR γ Cygni?)
- 3EG 1835+59
- 3C279 lowest 5σ detection
- 3EG 1911-2000 (AGN)
- Mrk 421
- Weakest 5σ EGRET source

During the all-sky survey, GLAST will have sufficient sensitivity after one day to detect (5σ) the weakest EGRET sources.

*zenith-pointed
^"rocking" all-sky scan: alternating orbits point above/below the orbit plane

Instruments: LAT and GBM

GLAST LAT Collaboration

United States

- California State University at Sonoma
- University of California at Santa Cruz - Santa Cruz Institute of Particle Physics
- Goddard Space Flight Center – Laboratory for High Energy Astrophysics
- Naval Research Laboratory
- Stanford University – Hanson Experimental Physics Laboratory
- Stanford University - Stanford Linear Accelerator Center
- Texas A&M University – Kingsville
- University of Washington
- Washington University, St. Louis

France

- Centre National de la Recherche Scientifique / Institut National de Physique Nucléaire et de Physique des Particules
- Commissariat à l'Energie Atomique / Direction des Sciences de la Matière/ Département d'Astrophysique, de physique des Particules, de physique Nucléaire et de l'Instrumentation Associée

Italy

- Istituto Nazionale di Fisica Nucleare
- Istituto di Fisica Cosmica, CNR (Milan)

Japanese GLAST Collaboration

- Hiroshima University
- Institute for Space and Astronautical Science
- RIKEN

Swedish GLAST Collaboration

- Royal Institute of Technology (KTH)
- Stockholm University

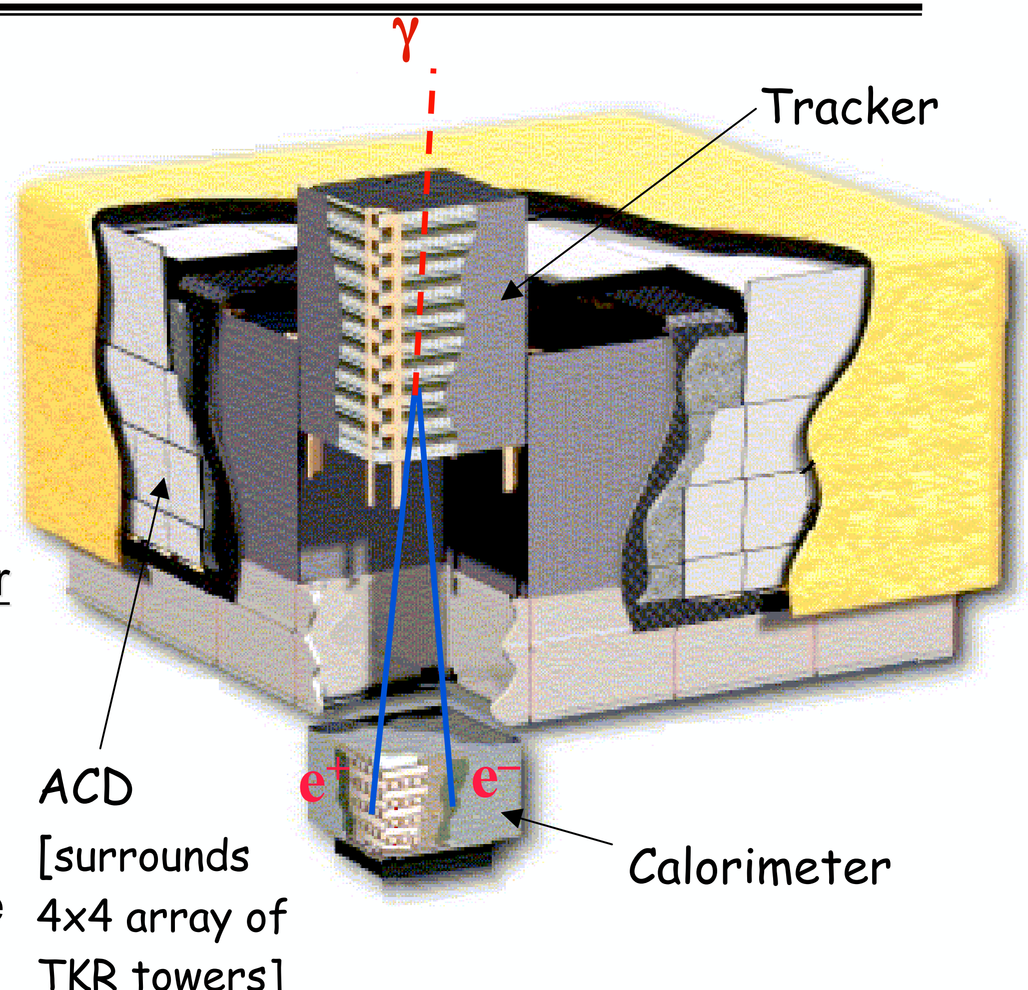
PI: Peter Michelson (Stanford & SLAC)

124 Members (including 60 Affiliated Scientists, plus 16 Postdoctoral Students, and 26 Graduate Students)

LAT Project is a partnership between NASA and DOE, with international contributions from France, Italy, Japan and Sweden. Managed at Stanford Linear Accelerator Center (SLAC).

Overview of LAT

- Precision Si-strip Tracker (TKR)
  18 XY tracking planes. Single-sided silicon strip detectors (228 μm pitch) Measure the photon direction; gamma ID.
- Hodoscopic CsI Calorimeter(CAL)
  Array of 1536 CsI(Tl) crystals in 8 layers. Measure the photon energy; image the shower.
- Segmented Anticoincidence Detector (ACD) 89 plastic scintillator tiles. Reject background of charged cosmic rays; segmentation removes self-veto effects at high energy.
- Electronics System Includes flexible, robust hardware trigger and software filters.



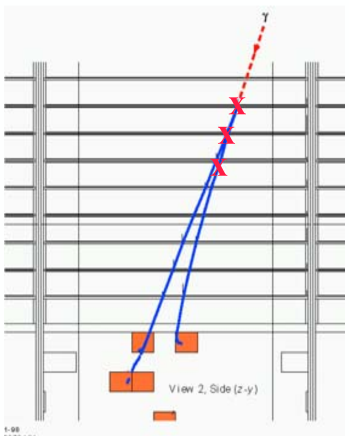
Systems work together to identify and measure the flux of cosmic gamma rays with energy 20 MeV - >300 GeV.

Instrument Triggering and Onboard Data Flow

Level 1 Trigger

Hardware trigger based on special signals from each tower; initiates readout

Function: • "did anything happen?"
• keep as simple as possible



- **TKR 3 *x•y* pair planes in a row****
  workhorse γ trigger

OR

- **CAL:**
  LO – independent check on TKR trigger.
  HI – indicates high energy event ⟶ disengage use of ACD.

Upon a L1T, all towers are read out within 20μs

Instrument Total L1T Rate: <4 kHz>

****4 kHz orbit averaged without throttle (1.8 kHz with throttle); peak L1T rate is approximately 13 kHz without throttle and 6 kHz with throttle).**

On-board Processing

full instrument information available to processors.

Function: reduce data to fit within downlink

Hierarchical process: first make the simple selections that require little CPU and data unpacking.

- **subset of full background rejection analysis, with loose cuts**
- **only use quantities that**
  - **are simple and robust**
  - **do not require application of sensor calibration constants**

- **complete event information**
- **signal/bkgd tunable, depending on analysis cuts:**
  γ:cosmic-rays ~ 1:~few

Total L3T Rate: <25-30 Hz>

(average event size: ~8-10 kbits)

On-board science analysis:
transient detection (AGN flares, bursts)

Spacecraft

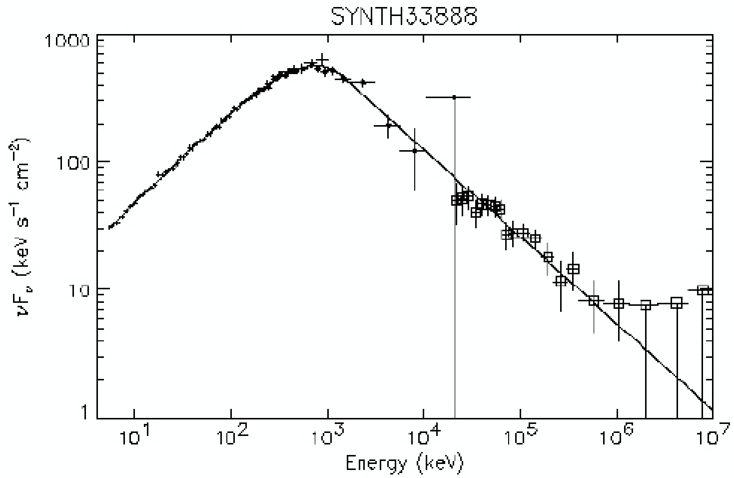
GBM (PI: Meegan)

- **provides spectra for bursts from 10 keV to 30 MeV, connecting frontier LAT high-energy measurements with more familiar energy domain;**

Simulated GBM and LAT response to time-integrated flux from bright GRB 940217

Spectral model parameters from CGRO wide-band fit

1 NaI (14 º) and 1 BGO (30 º)



- **provides wide sky coverage (8 sr) -- enables autonomous repoint requests for exceptionally bright bursts that occur outside LAT FOV for high-energy afterglow studies (an important question from EGRET);**
- **provides burst alerts to the ground.**

GBM Collaboration

National Space Science & Technology Center

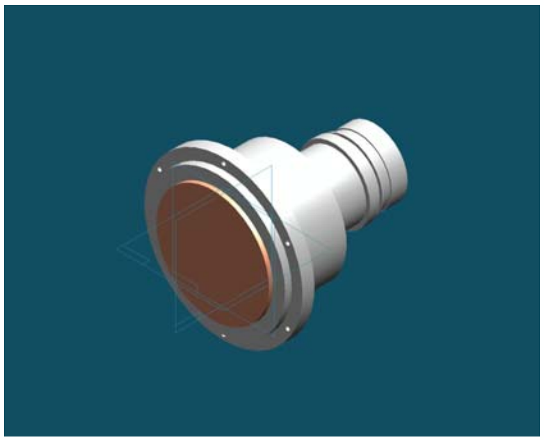
University of Alabama in Huntsville	NASA Marshall Space Flight Center	Max-Planck-Institut fuř extraterrestrische Physik
Michael Briggs	Charles Meegan (PI)	Giselher Lichti (Co-PI)
William Paciesas	Gerald Fishman	Andreas voṇ Keinlin
Robert Preece	Chryssa Kouveliotou	Volker Schonfelder
		Roland Diehl

On-board processing, flight software, systems engineering, analysis software, and management

Detectors, power supplies, calibration, and analysis software

GBM Instrument Design: Major Components

12 Sodium Iodide (NaI) Scintillation Detectors



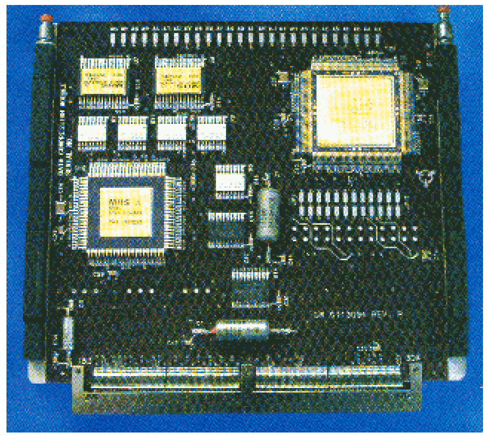
Characteristics

- 5-inch diameter, 0.5-inch thick
- One 5-inch diameter PMT per Det.
- Placement to maximize FoV
- Thin beryllium entrance window
- Energy range: ~5 keV to 1 MeV

Major Purposes

- Provide low-energy spectral coverage in the typical GRB energy regime over a wide FoV
- Provide rough burst locations over a wide FoV

Data Processing Unit (DPU)



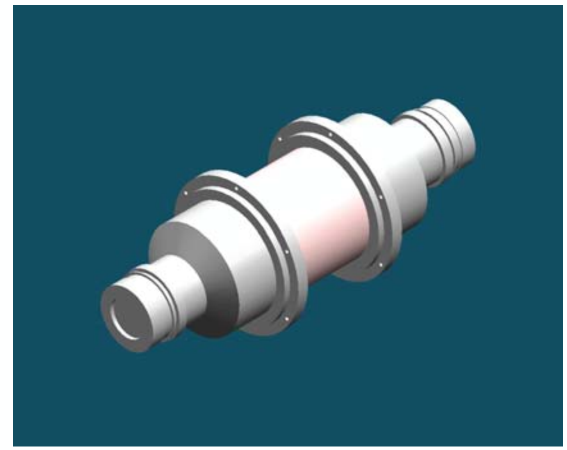
Characteristics

- Analog data acquisition electronics for detector signals
- CPU for data packaging/processing

Major Purposes

- Central system for instrument command, control, data processing
- Flexible burst trigger algorithm(s)
- Automatic detector/PMT gain control
- Compute on-board burst locations
- Issue r/t burst alert messages

2 Bismuth Germanate (BGO) Scintillation Detectors



Characteristics

- 5-inch diameter, 5-inch thick
- High-Z, high-density
- Two 5-inch diameter PMTs per Det.
- Energy range: ~150 keV to 30 MeV

Major Purpose

- Provide high-energy spectral coverage to overlap LAT range over a wide FoV

Summary

- GLAST Science is exciting!
  - Highest-ranked mid-size mission in the most recent National Academy of Sciences "Decadal Survey" of Astronomy and Astrophysics.
  - Positively peer-reviewed by Particle Physics community (Scientific Assessment Group for Experiments in Non-Accelerator Physics (SAGENAP)
- GLAST will address many important questions:
  - What is going on around black holes? How do Nature's most powerful accelerators work? (are these engines really black holes?)
  - What are the unidentified sources found by EGRET?
  - What is the origin of the diffuse background?
  - What is the high energy behavior of gamma ray bursts?
  - What else out there is shining gamma rays? Are there further surprises in the poorly measured energy region?
  - When did galaxies form?
- Large menu of "bread and butter" science, and Large discovery potential.

WELCOME ABOARD, SPECTRUM ASTRO!!

Backup material

Context: Mission Repointing Plan

Summary of plan

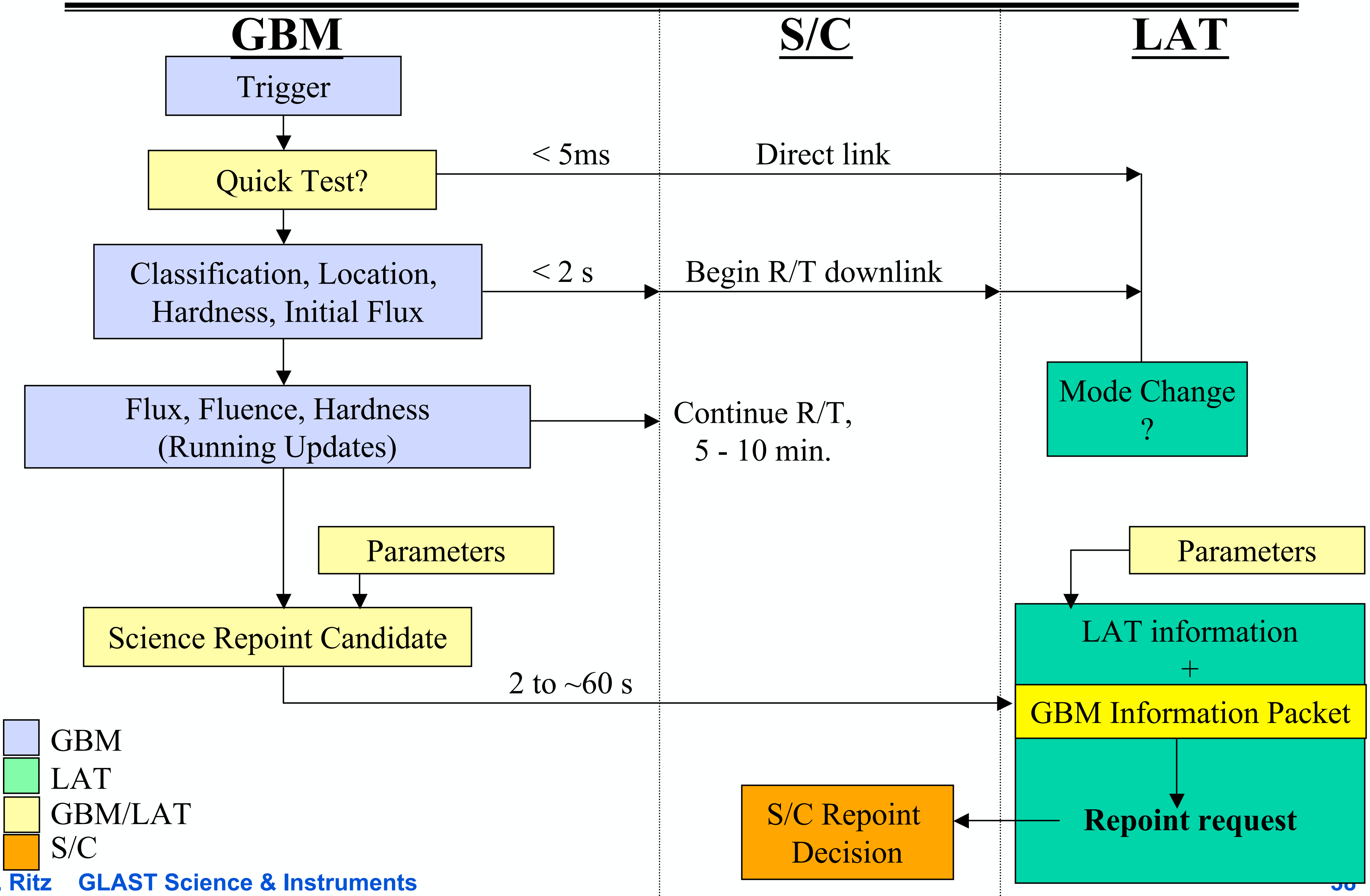
During all-sky scanning operations, detection of a sufficiently significant burst will cause the observatory to interrupt the scanning operation autonomously and to remain pointed at the burst region during all non-occulted viewing time for a period of 5 hours (TBR). There are two cases:

1. **The burst occurs within the LAT FOV.** **If the burst is bright enough that an on-board analysis provides >90% certainty that a burst occurred within the LAT FOV, the observatory will slew to keep the burst direction within 30 degrees (TBR) of the LAT z axis during >80% of the entire non-occulted viewing period (neglecting SAA effects). Such events are estimated to occur approximately once per week.**

2. **The burst occurs outside the LAT FOV.** **Only if the burst is exceptionally bright, the observatory will slew to bring the burst direction within 30 degrees (TBR) of the LAT z axis during >80% of the entire non-occulted viewing period (neglecting SAA effects). Such events are likely to occur a few times per year.**

After six months, this strategy will be re-evaluated. In particular, the brightness criterion for case 2 and the stare time will be revisited, based on what has been learned about the late high-energy emission of bursts.

Burst Repoint Candidate Path



GBM Instrument Requirements

Top-Level GBM Instrument Requirements

Parameter	Requirement	Goal	BATSE
	σ		
	σ		
	σ		
			π
	μ	μ	μ